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The Equatorial Ionosphere

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The equatorial ionosphere is a small but scintifically interesting part of the spacc plasma environment of the Earth. The equatorial 'spread F', the equatorial electrojet and the 'equatorial anomaly' in the F-region plasma distribution are the most important special phenomena of the equatorial ionosphere. The above phenomena are caused by the plasma electrodynamic processes arising from the specific equatorial geometry of the electric fields being orthogonal to the nearly horizontal geomagnetic field lines. The present status of knowledge about the equatorial ionospheric phenomena is reviewed. Some of the unresolved questions are briefly discussed.

1. Introduction

For the purpose of the present article, the 'equatorial ionosphere' is defined as the region between ±20° geomagnetic latitudes and extending from 60 km to 2000 km. The equatorial ionosphere is one important part of the ionosphere-magnetosphere plasma environment of the earth. Its importance derives from the scintifically fascinating phenomena occurring in this region of space and also from the practical implications of the phenomena to the communication circuits involving the propogation of signals through this medium.

Most of the special features of the equatorial ionosphere can be considered as subsets of three major phenomena: (i) the Equatorial Spread F (ESF), (ii) the Equatorial Electrojet (EJJ) and (iii) the Equatorial Anomaly(EA). All three phenomena in turn result from the orthogonality of the almost horizontal geomagnetic field lines and the electric fields threading the ionosphere in the vicinity of the dip equator. Studies in the past five decades have revealed the fascinating and bewildering complexity of the equatorial phenomena. Through the combination of experimental, morphological and theoretical studies, immense advances have been made in understanding the relevant physical processes. A brief overview of the current status of our knowledge on the equatorial ionosphere is presented in this paper along with a mention of some unresolved problems.

2. Equatorial Spread F

Starting from the first definitive description of the 'equatorial Spread F' (ESF) by Berkner and Wells[1] in 1934, scientific studies of this phenomenon have spanned over half a century. Progress in understanding the true nature of the phenomenon has been painfully slow until the last decade; and then the full power of modern technologies like high power radars, rocket soundings, satellite measurements, and fast computers has been put to good use in unravelling several intricate facts of this complex phenomenon.

The first major element of the modern scenario of ESF is the 'plume' structures revealed by VHF Radar observations at Jicamarca[2]. One typical observation is shown in Fig.1. The 3-metre size plasma irregularities

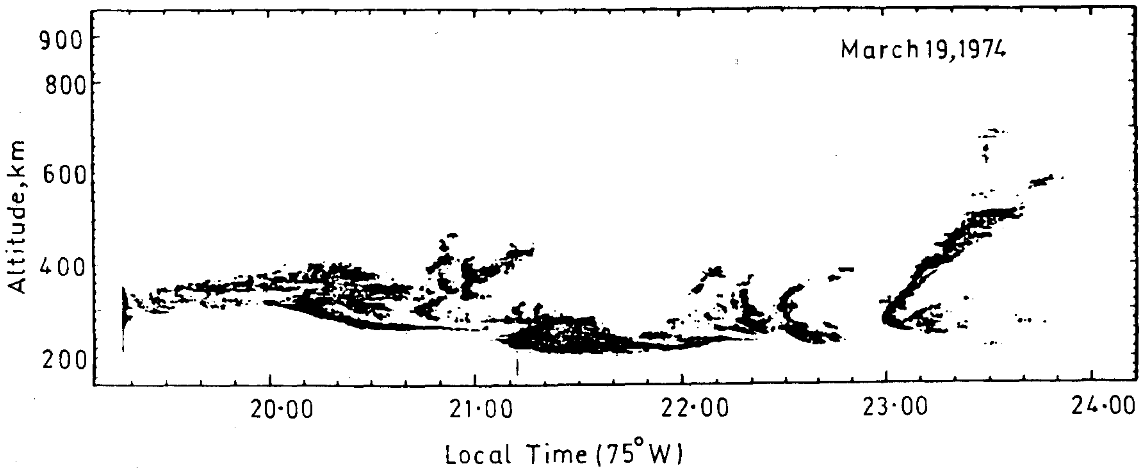

Fig.1 — Time - height cross-section of backscatter signals from 3-m size ionization irregularities in F-region at Jicamarca, Peru. The upward and downward movements of backscattering regions and their total disappearance for a brief period around 2255 hrs. are to be noted (Woodman and La Hoz 1976).

responsible for the backscatter of 50 MHz signals almost always appear, in the late evening, first at the bottom side of the F-region where the gradient of electron density (N_e) is quite large and positive. Then they seem to move upward slowly sometimes and quite rapidly at other times; they also move downward occasionally and even disappear for sometime before reappearing again. The observed rapid growth or spread of the 3-m size irregularities throughout the F-region, including the topside, raised important questions about the validity of 'spread F' theories[3].

The second major element of recent observations is the detection of plasma 'bubbles' which are regions of large depletions of plasma. Incoherent scatter radar observations at Kwajalein (dip lat. 4.3°N), and rocket and satellite observations have shown that the 'bubbles' have typical vertical dimensions of 10-20 km, horizontal dimensions of 100-200 km transverse to the magnetic field lines, and they are aligned along the geomagnetic field lines over distances of several hundred kilometres[4-6]. Fig.2 shows the height structure of N_e as measured with the I.S. Radar at Kwajalein and it reveals the rapid development, including the upward move-

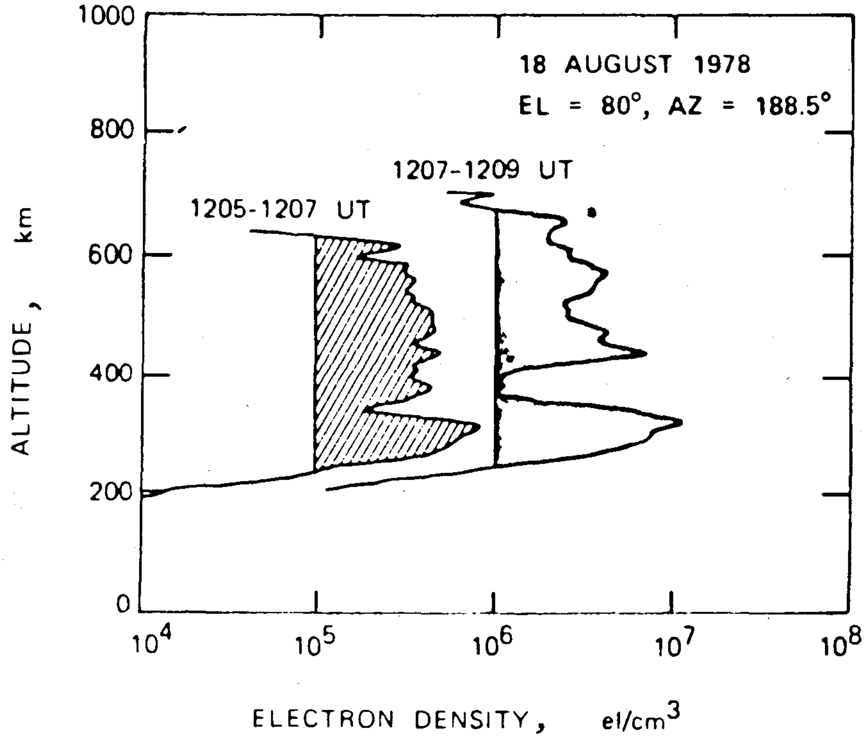

Fig.2 — Height profiles of electron density at Kwajalein (4.3°N dip latitude) as measured with the ALTAIR Incoherent Scatter radar during spread F conditions (Tsunoda 1980).

ment, of a plasma depletion region. The plasma density in the 'bubble' is smaller than that in the surrounding medium by an order of magnitude. Satellite measurements have revealed reductions by 2-3 orders of magnitude in some cases. The field-aligned nature and extent of the bubbles is shown schematically in Fig.3 as deduced from the topside sounder

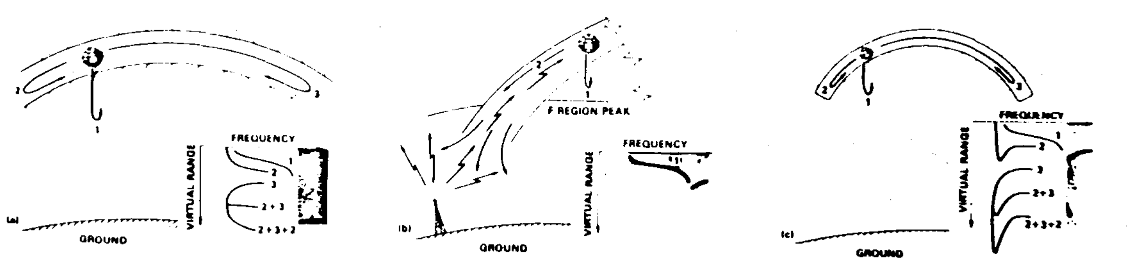

Fig.3 — Schematic of field-aligned large scale plasma depletions as deduced from topside ionograms (Dyson and Benson 1978).

ionograms[7,8]. Such field-aligned extension of the depletion of plasma is clearly seen in I.S. Radar mapping of the depletions in the magnetic meridional plane at Kwajalein. Observations at Kwajalein also indicate that the field-aligned bubbles occur over longitude sectors as wide as 10 -20° in conformity with satellite observations.

ALTAIR radar (155 MHz) observations at Kwajalein also showed unambiguously that the small scale irregularities (1-m scale size) responsible for the backscatter echoes ('plumes') occur in spatial coincidence with the 'bubbles'[5,6]. Fig.4 shows the observed association of small scale irregularities with the regions of plasma depletions, as observed with the ALTAIR radar. The spatial resolution of the radar was not adequate to check whether the small scale irregularities were located on the steep gradients ('walls') of the bubbles, and this question is yet to be settled from further measurements with rocket-borne instruments.

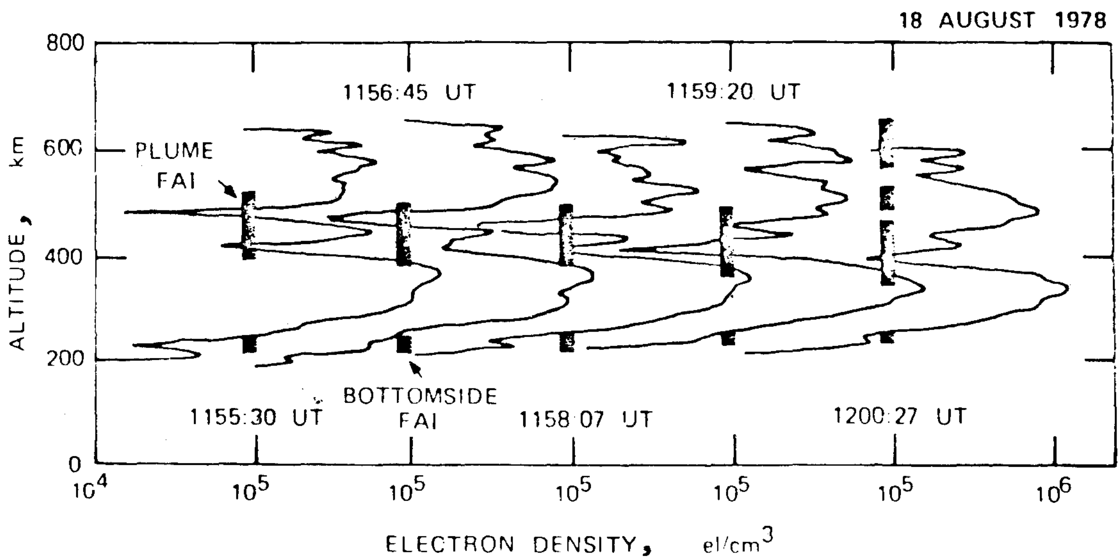

Fig.4 — Height profiles of electron density exhibiting large depletions in narrow height regions; dark vertical bands represent the regions from which intense backscatter signals at 155 MHz (i.e. from 1-m size irregularities) were observed at Kwajalein (Tsunoda 1980).

The third aspect of observations in the last several years is the association of scintillations in the VHF, UHF and GHz bands with the radar-observed 'plume' structures, indicating thereby that the km size irregularities (responsible for scintillations) and the metre-size irregularities (responsible for plumes) coexist. Such simultaneous presence of the large and small scale sizes in turn supports the theoretical models in which the small scale irregularities are generated from the larger ones through casacade or non-linear processes (Beyond the above remark, the very important aspect of ionospheric scintillations caused by ESF is omitted in this article).

Very impressive advances were made in the theoretical modelling of different physical processes which can give rise to 'spread F' irregularities and the plasma 'bubbles'[9,10]. D.F. Martyn's[11] concept of an ionization irregularity (i.e. a region of reduced electron density) getting amplified as it rises towards the F-region peak has been extended to show that the rise and amplification can continue even in the topside of the F-region peak. The difficulty of using Martyn's concept or the linear Rayleigh-Taylor (R-T) instability mechanism to understand topside spread F has been successfully overcome in the numerical models

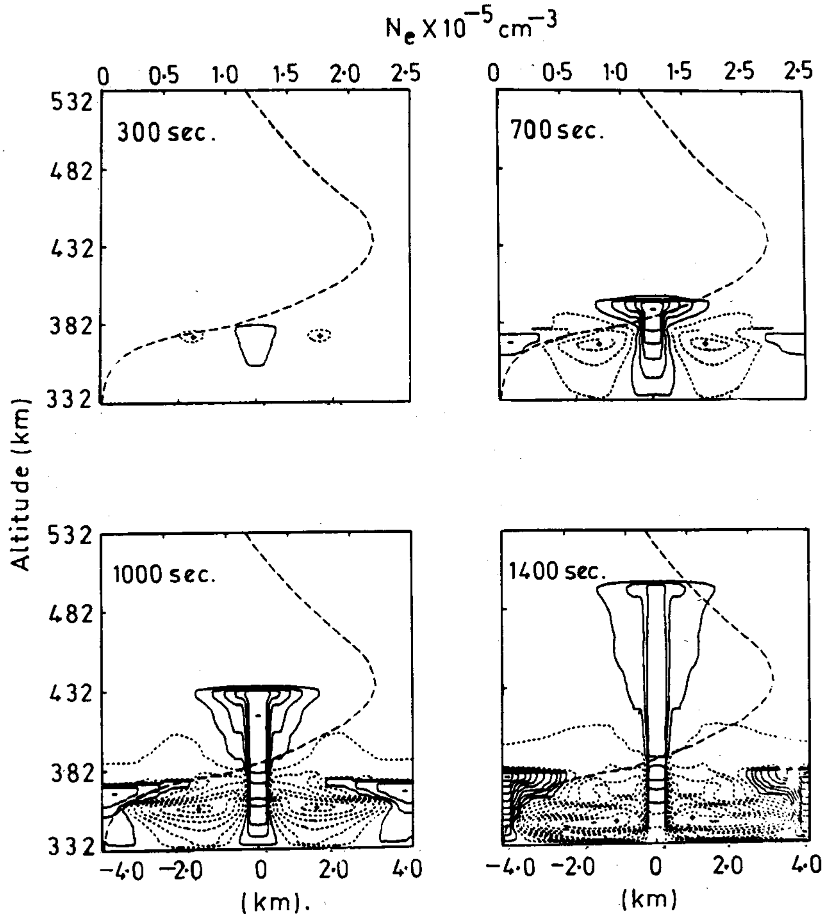

Fig.5 — Theoretical models of the time evolution of plasma 'bubbles' (depletion regions) in the equatorial F-region. The rapid rise of the bubble into the topside ionosphere is to be noted. Contour plots of constant fractional deviation in electron density ($\Delta N_e/N_e$) are shown. Dotted lines with plus sign inside and solid lines with minus sign inside indicate enhancement and depletion over the ambient N_e which is depicted by the broken line. The lower horizontal axis is the east-west range and the magnetic field is perpendicular to the plane of the figure, out of the figure (Ossakow et al 1979).

where the collisional R-T instability process as well as the gradient drift instability process are incorporated along with non-linear interactions[9]. As a result of such modelling, the generation of the plasma bubbles (resulting in almost 100% depletion of plasma), their rise deep into the topside, the near simultaneous rapid growth of small scale irregularities in bottomside, near the peak and the topside of the F-region have been simulated successfully (Fig.5). In effect, one may say that the basic features of 'spread F' characteristics have been satisfactorily explained, on the basis of a 'heirarchy' of instabilities first suggested by Haerendel[12]. However, several basic questions of importance still remain unanswered. Some examples of which are:

(i) In all the theories and numerical models an initial 'seed' perturbation is assumed at the bottomside. What physical process or phenomenon provides this 'seed' perturbation?

(ii) What are the conditions or parameters which trigger ESF, sustain it and cause its decay?

(iii) What is the precise relationship between the large scale bubbles and the small scale irregularities?

(iv) What are the precise saturation mechanisms for the small scale irregularities?

(v) What are the roles of neutral winds and electric fields in controlling or triggering ESF? (Recent observations in India[13] on the structure of F-region electric fields are significant in this context).

(vi) What is the nature and extent of the E-region influence on the ESF?

The above list is not exhaustive. The field is wide open to researchers who want to carry out innovative studies on this complex phenomenon of the equatorial ionosphere.

3. Equatorial Electrojet

The equatorial electrojet is an intense band of east-west electric current flowing within ±3° of the magnetic dip equator around 105 km altitude. The ground-level magnetic field signatures of this intense current were recorded by the magnetometer at Huancayo, Peru, as early as 1922; but the varied implications of this interesting phenomenon were recognized only in 1950s and 1960s. The name 'Equatorial Electrojet' (EEJ) was suggested by Sidney Chapman[14] in 1951, much later than its initial discovery in terms of the magnetic fields signatures. Martyn[15] pointed out as early as 1949 that the EEJ was the consequence of the vertical polarisation electric field set up in the E-region near the magnetic equator due to the presence of mutually orthogonal north-south magnetic and east-west electric fields. He pointed out that this secondary vertical polarisation field (E_p) could generate a much larger Hall current than the Pedersen current caused by the primary east-west electric field (E_y). Fig. 6 shows the height structure of the vertical

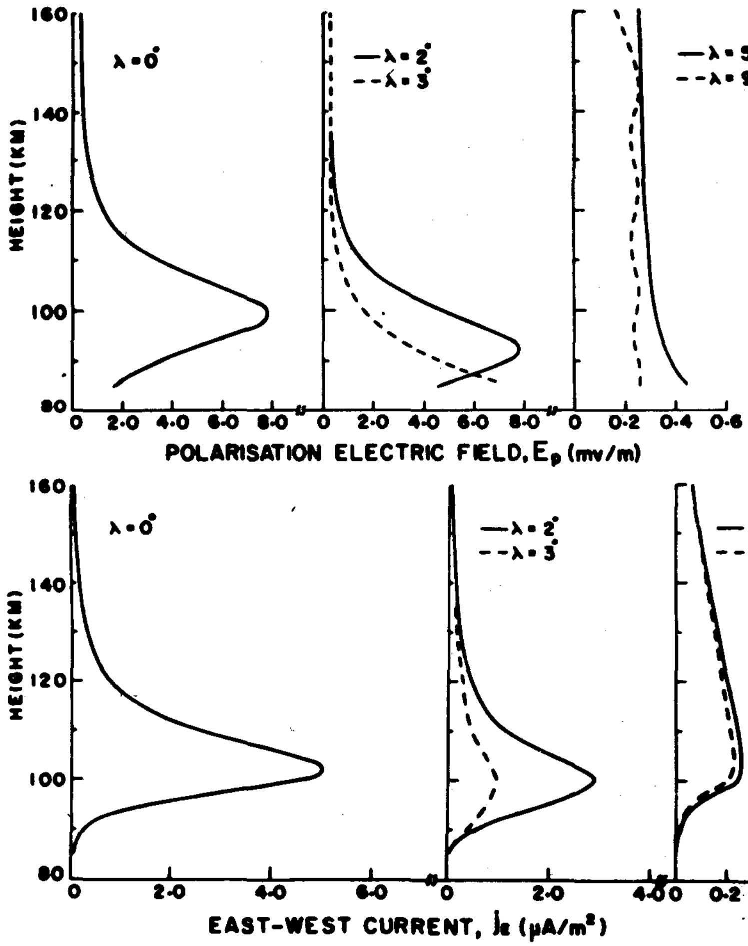

Fig.6 — Height structure of the polarization electric field (E_p) and the current density (j) in and outside the equatorial electrojet

polarization field (E_p) and the current density (j) within and outside the electrojet latitudes. The peak values of both E_p and j increase by a factor of about 27 from 9° to 0° geomagnetic latitude. The corresponding increase in the ground-level magnetic field perturbation due to the above currents is only by a factor of 3 approximately because the magnetic field perturbation is a spatially integrated effect[16,17].

The morphological features of the equatorial electrojet as reflected in the ground-level magnetic field variations are well documented[18,19]. The vertical structure of the current in the EEJ as determined from rocket-based measurements is described in the relevant papers[17,20]. The main results of VHF and HF radar studies on the EEJ are summarized in the review articles by Fejer and Kelley[10], Reddy[21,22] and Crochet[23].

In terms of the physics of the equatorial electrojet, three aspects have turned out to be the most interesting: (i) the plasma instabilities, (ii) the electric fields and (iii) the local interaction of height-varying winds. Starting from early 1960's, extensive measurements were made with a VHF Radar at Jicamarca, Peru, on several aspects of the two-stream instability and the gradient drift or cross-field instability which give rise to ionization irregularities of type I and type II respectively. Rocket measurements in India brought out the spectral characteristics of the type I and type II irregularities[24-27]. Starting from the basic theoretical work of Farley[28] on the two-stream instability, there has been a parallel development of theory to explain the observed characteristics of type I and type II irregularities. Some of the outstanding questions about the plasma instabilities in the EEJ seem to have been resolved in the recent work of Sudan[29] who worked out a unified theory of type I and type II irregularities. Reviews of the experimental and theoretical work on plasma instabilities in the EEJ can be found in Fejer and Kelley[10], Sudan[29] and references therein.

The electric fields in the EEJ can be classified into (a) the steady or slowly varying electric fields which drive the electrojet and (b) the high frequency small scale electric fields associated with the plasma irregularities. Some limited number of measurements have been made on the latter with rocket-borne electric field probes (see Kelley and Fejer[10]; Prakash et al[30]). The electric fields driving the electrojet have been deduced from VHF backscatter radar measurements and from the incoherent scatter radar measurements[31-35].

The study of electric fields in the electrojet has turned out to be very valuable from different points of view. Fig.7 shows the time variations of the mean Doppler frequency f_D of 55 MHz radar signals backscattered from the equatorial electrojet at Thumba in India. The f_D values are directly proportional to the east-west electric field (E_y) driving the electrojet current; a negative f_D represents an eastward electric field. The progressive increase of the fluctuating component of f_D with increasing magnetic activity (as represented by A_p values) shows that an electric field other than the dynamo electric field generated by global wind system in the E-region becomes increasingly important on magnetically disturbed days. In panel (d) of Fig.7, there is an indication that the normal eastward electric field in daytime seen in (a) is suppressed on the highly disturbed day. This additional electric field of disturbed days has its origin in the magnetospheric processes or the magnetospheric-ionospheric interaction processes at auroral-polar latitudes. The short period fluctuations or the bay-type disturbances in the EEJ were shown to be closely related to corresponding disturbances in the auroral electrojets[36,37]. A striking example of a very sensitive response of the electric field in the EEJ to the solar wind-magnetospheric interactions is shown in Fig.8. In this figure, a large decrease of the electric field in the EEJ at Thumba

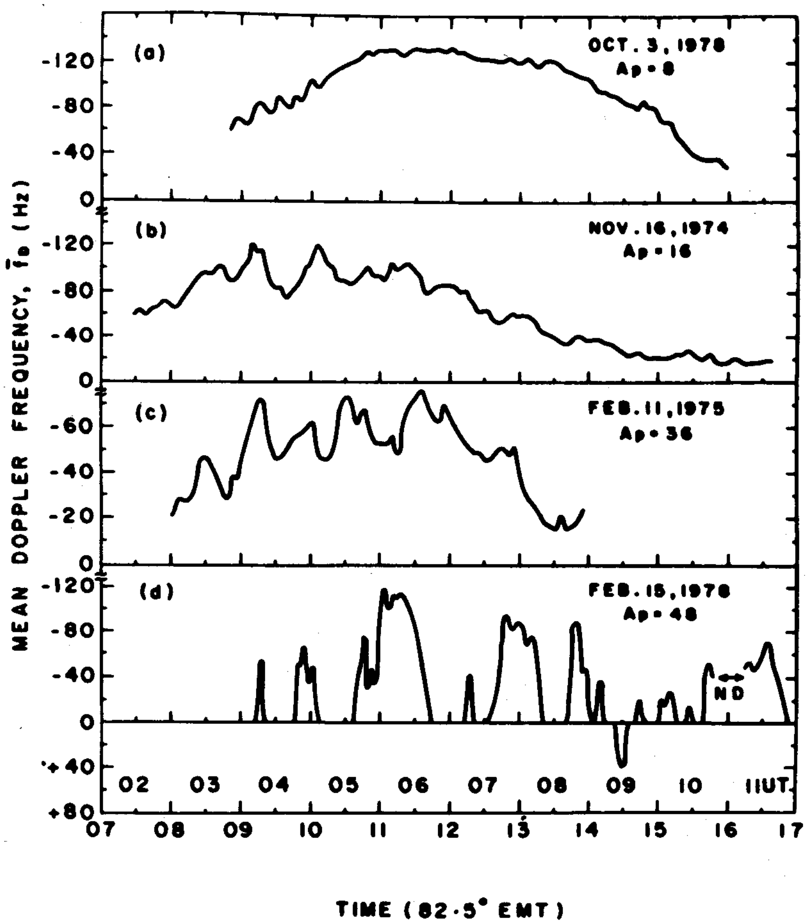

Fig.7 — Daytime variations of electric field in the equatorial electrojet as represented by the mean Doppler frequency $\overline{f}_D$ of the backscatter radar signals on different days

in phase with the decrease of the polar cusp latitude is depicted during a geomagnetic storm. Thus, the electric field changes in the EEJ can provide valuable clues to the understanding of some aspects of the solar wind-magnetosphere-ionosphere interactions. Research work on this important aspect is in progress at VSSC[22,38].

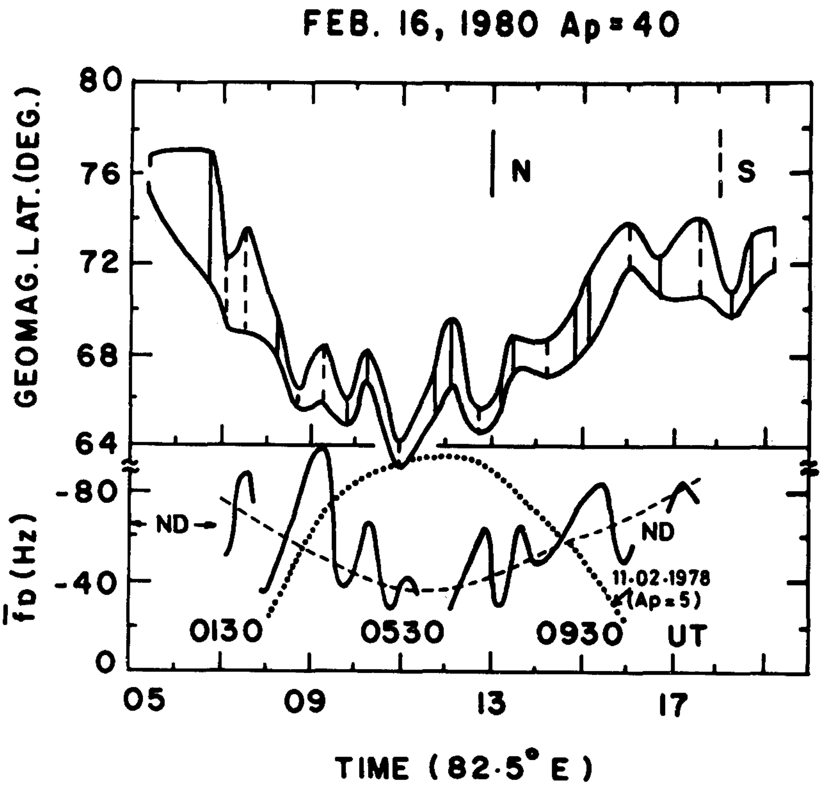

Fig.8 — In-phase variations of the mean Doppler frequency $\bar{f}_D$ of backscatter radar signals from electrojet at Thumba and the latitude of the polar cusp. $\bar{f}_D$ is proportional to the electric field in the electrojet (Somayajulu et al 1985).

Systematic measurements at Jicamarca on ionization drifts in the F-region have provided valuable information on the diurnal and seasonal variations of electric fields in the equatorial E-region (e.g. Fejer et al[33].)

Theoretical studies in the last decade have shown that height-varying winds within the equatorial electrojet can interact with the plasma in such a way that polarisation electric fields (which are additional to the field generated by E_y referred to earlier) are generated in the magnetic meridional plane. The height-varying winds can originate in propagating tides and gravity waves. The electric fields generated by such local interaction of shearing winds can have large variations in the vertical over typical scales of 5-20 km. Correspondingly, there are accompanying meridional currents and east-west (Hall) currents with short vertical scale variations[14,39-42]. Therefore, the height structure and the latitude structure of the electric fields and currents in the EEJ can deviate considerably from the normal structures expected in case of a large scale curl-free east-west electric field E_y as the driving source for the electrojet. Experimental evidence for such distortions in the height structure has been found from the VHF radar observations at Thumba[35,43], while distortions in the latitude structures are observed in the ground-level magnetometer recordings[44].

One extreme manifestation of the mesoscale or regional scale deviation of the electrojet from its normal structure is the counter electrojet (CEJ) phenomenon. Partial counter electrojets are associated with particular values of the lunar phase[45] and apparently they are caused by the additive effect of the lunar tide-generated electric field in the equatorial dynamo region. The stronger CEJ events in which the normal daytime eastward current reverses direction seem to occur in an unpredictable manner, though they have a clear seasonal and solar cycle dependence on a statistical basis[46]. We do not yet have an understanding of the precise mechanism which is responsible for the observed unpredictable refersals of the electric field in the EEJ during the CEJ events (see Reddy[21,22] for further detailed discussion).

The basic physical processes driving the equatorial electrojet and the associated plasma instabilities are fairly well understood. Nevertheless, there are several basic questions which can be answered only through experimental and theoretical studies on the electrojet. In case of plasma instabilities, the physics of saturation mechanisms are yet to be understood; the relationship or interactions between the gradient drift (type II) and the two-stream (type I) irregularities is to be quantified; the relative importance of cascading and non-linear processes in the generation of small scale irregularities is to be understood; and adequate measurements of the electric field structures associated with various scales of irregularities are to be made. In case of the electric fields driving the electrojet current, effects of solar wind-magnetosphere-ionosphere interactions on the EEJ electric fields are yet to be studied in quantitative detail for understanding some basic aspects of the above interactions, The physics of counter electrojet events is yet to be understood. The equatorial electrojet is a sensitive medium where characteristic changes in the electric fields and currents are produced by upward propagating tides and gravity waves from the lower atmospheric regions, by the dynamo electric fields at E-region levels, and by the downward penetrating electric fields and currents from the distant magnetosphere. Quantification and interpretation of the above changes constitute a valuable method for understanding several aspects of the much larger space domain embedding the equatorial electrojet.

4. Equatorial Anomaly

The 'equatorial anomaly' is the name given to the peculiar latitude variation of the maximum electron concentration (N_m) in the ionospheric F-region which shows a minimum of N_m at the dip equator and two maxima on either side around 17° dip latitude[47]. Prof.S.K. Mitra[48] pointed out in 1946 that the diffusion of plasma along the geomagnetic field-lines to both sides of the dip equator could lead to enhanced concentration of ionozation around 17° dip latitude as observed. In 1955, D.F. Martyn[11, 49] pointed out the importance of the upward electromagnetic drift of ionization near the magnetic equator (in addition to the downward diffusion along field lines) in causing the observed 'anomalous' distribution of ionization with latitude.

The above basic processes were incorporated into various theoretical models [50,51] to explain successfully the observed features of the equatorial anomaly. Both morphological descriptions[52-54] and better theoretical modelling incorporating more realistic ionospheric paramters progressed with time[55-57]. Finally the north-south asymmetry of the anomaly was also successfuolly explained by incorporating the effects of neutral winds in the F-region. There are no specific questions remaining unanswered about the physics of this historically important phenomenon.

A detailed knowledge of the equatorial anomaly and its short and long term variabilities is important in view of its influence on other physical processes in the equatorial ionosphere. It is also important in estimating the refractive effects on the transionospheric signals.

5. Other Topics

In this article of limited size, all topics relating to equatorial ionospheric processes are not included. Particular mention should be made of equatorial ionospheric scintillations caused mainly by F-region irregularities. Extensive studies have been made in India using radio beacon experiments on the characteristics of the scintillations in the VHF and UHF bands and in the GHz band to a limited extent (e.g. Krishna Murthy et al[58]; Raghava Reddi et al[59]; Somayajulu[60]). Such studies are very valuable for understanding the spectral characteristics of the ionospheric irregularities and their relationship with other ionospheric parameters. Studies on scintillations are also important from the practical viewpoint of designing optimally the satellite-to-ground communication channels.

Travelling Ionospheric Disturbances (T.I.D's) in the equatorial ionosphere is another topic not covered in this article. The general morphology of equatorial F-region is also not included either for geomagnetically quiet or disturbed times.

The processes relating to D-region ionization and chemistry are not included mainly because of the absence of any distinctive features of the equatorial D-region.

Finally, the special features of the equatorial thermospheric structure and dynamics which may influence the equatorial ionosphere are also not presented in this article.

6. Indian Contributions

In presenting brief overviews of three major equatorial ionospheric phenomena in the earlier sections, the extent of the wide ranging contributions from India to the present body of knowledge on equatorial ionosphere might not have been brought out fully. In addition to the pioneering contributions by Prof. S.K. Mitra and his colleagues starting from 1930s, other schools of ionospheric research got established in the post-Independence period in India. A few ionosondes were installed for regular scientific data collection and several experiments were built by different groups. A variety of new findings relating to the low latitude ionospheric processes were published in standard scientific journals.

The bulk of research contributions from India on equatorial ionosphere can be broadly classified into three categories: (i) morphological studies, (ii) observational results from ground-based experiments and (iii) observational results from rocket-based experiments. Moreover, there has been a limited amount of theoretical work of excellent quality.

The morphological studies cover a wide range of topics: equatorial anomaly, equatorial F-region, equatorial spread F, magnetic storm effects on F-region, magnetic field variations due to equatorial electrojet and counter electrojet, equatorial sporadic E, lunar tides, etc.

The ground-based experiments produced very useful results on a variety of topics like the horizontal drifts of ionospheric irregularities, the vertical movements of ionospheric layers, ionospheric absorption, T.I.Ds, solar eclipse effects, total electron content, ionospheric scintillations, topside ionosphere, equatorial spread F, equatorial electrojet, airglow, and geomagnetic disturbance effects in the equatorial ionosphere etc.

The rocket experiments were instrumental in generating basic data on height profiles of electron densities in D-and E-regions of the equatorial ionosphere, in bringing out quantitative results on the spectral characteristics of ionization irregularities in the electrojet, electric current structure in the EEJ, electric fields and winds in the E-region and F-region, and in giving valuable data on O_2, NO, scattered Lyman-α and airglow.

From the above it is evident that the range of topics covered and magnitude of work done in India on equatorial ionosphere are quite impressive. A full review of the Indian contributions requires a major effort. Even a full listing of the references needs considerable time and effort. A list of publications on ionospheric physics by Indian scientists has been prepared on the occasion of Prof. S.K. Mitra Commemorative Seminar.

7. Concluding Remarks

In ionospheric research, the era of exploration and discovery is over. Presently, a focussed effort is being made to gain a definitive, quantitative understanding of the physical processes and to model them so that we increase our predictive capability with regard to this important part of the near space environment of the Earth. In case of equatorial ionosphere also, the future research on various aspects is to be guided by the following scientific objectives:

(i) Acquiring a quantitative understanding of the complex physical processes, and modelling them for prediction purposes.

(ii) Generating detailed morphological descriptions of the equatorial ionosphere so that the corrections for refractive effects and scintillation effects can be applied in case of trnsionospheric signals between the ground and the spacecraft or the radio sources.

(iii) Understanding a variety of plasma processes like the electrodynamics of the plasma and the constituent particles, instabilities, wave-particle interactions, excitation and propagation of electrostatic, hydromagnetic and electromagnetic waves in different frequency bands.

(iv) Understanding some relevant processes in the lower regions of the Earth's atmosphere through their effects in the ionosphere.

(v) Understanding the large scale phenomena in the distant regions of the Earth's space environment, like the outer reaches of the magnetosphere and interplanetary space, through the local effects in the equatorial ionosphere.

(vi) Interpreting the ionospheric signatures of short term and long term changes of the solar and solar-planetary environment.

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